Xenon Doping of Liquid Argon

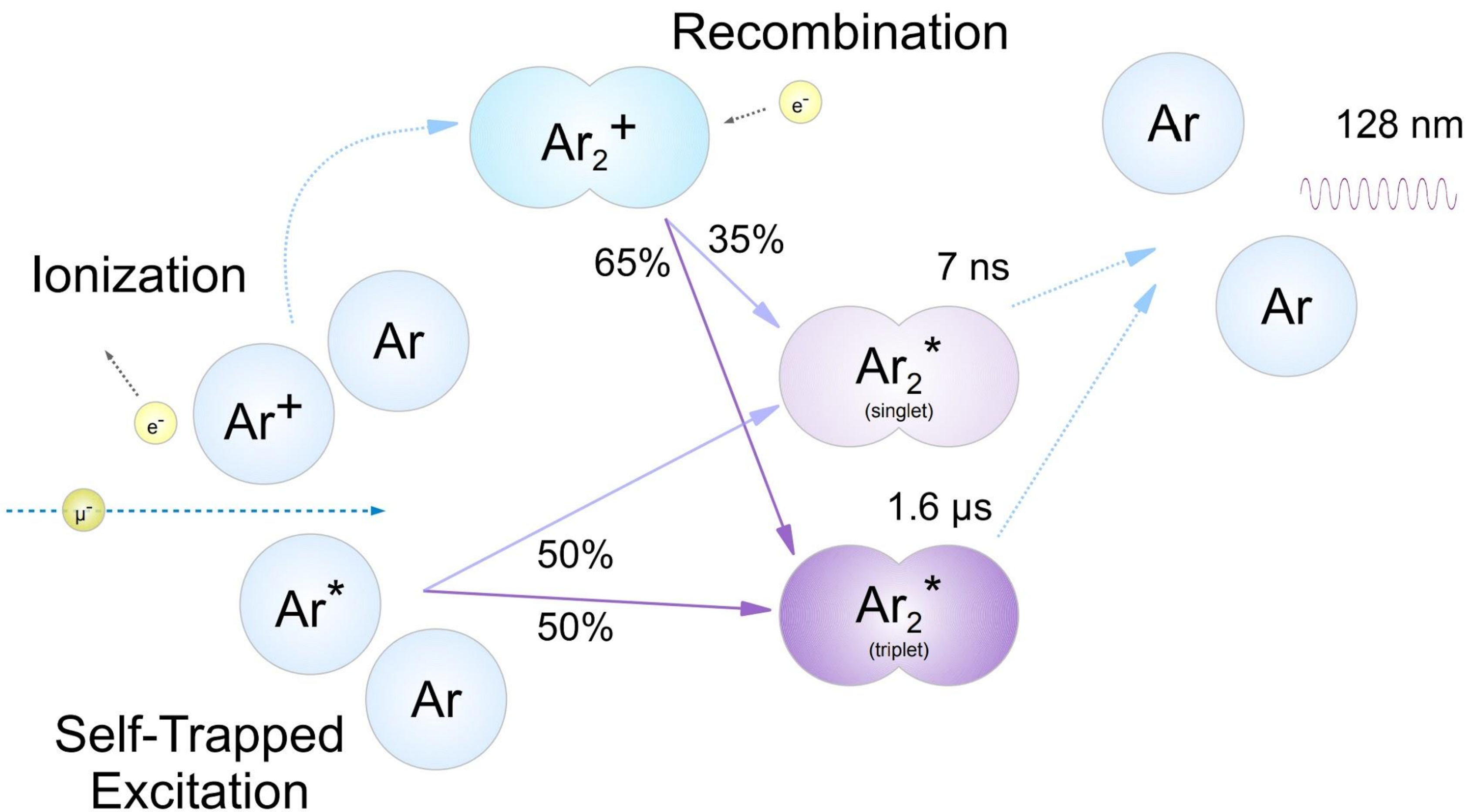
Denver Whittington, Syracuse University

DUNE Module of Opportunity Workshop

Nov. 12, 2019

Liquid Argon Scintillation Mechansim

- Excitation of short-lived argon excited molecular states.



Effects of Xenon Dopant

Collisional energy transfer from argon excimer to xenon excimer

$$Ar_2^* + Xe \rightarrow ArXe^* + Ar,$$

$$ArXe^* + Xe \rightarrow Xe_2^* + Ar,$$

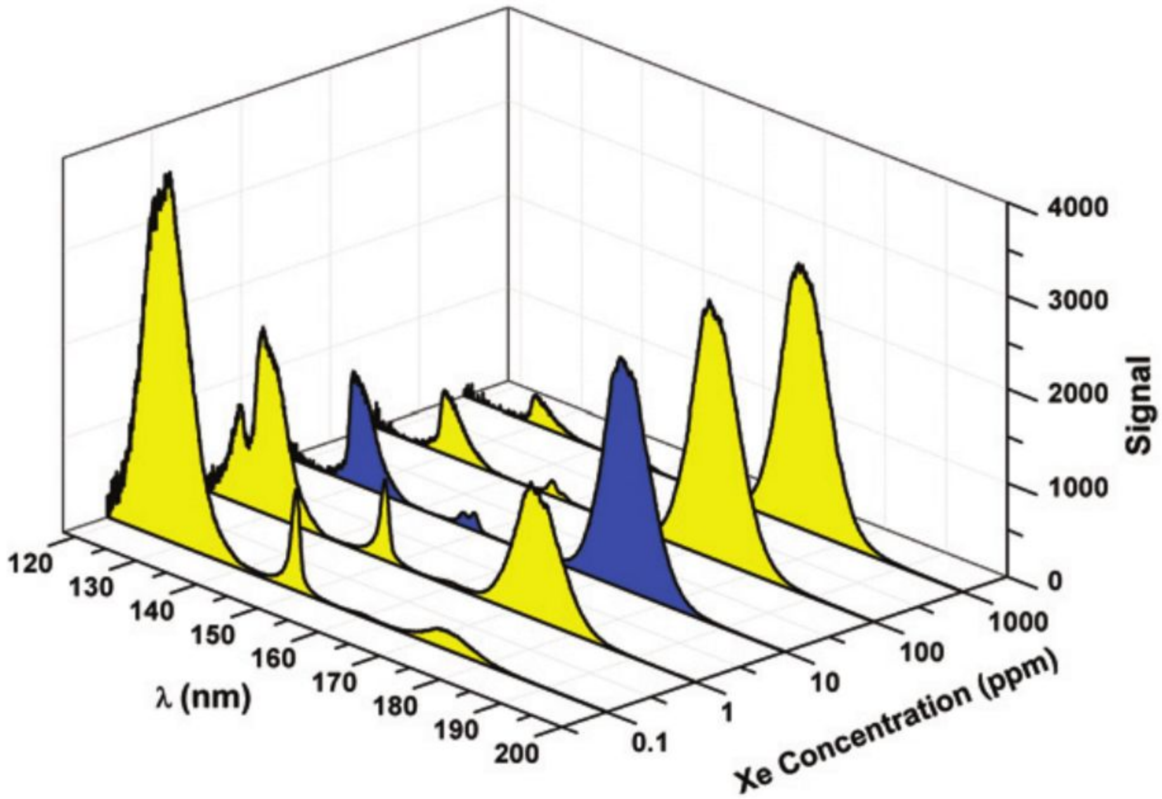
$$Xe_2^* \rightarrow 2Xe + \gamma_{174}$$

Happens on a faster timescale than Ar triplet lifetime.

- Triggers triplet emission to produce a faster signal
- Converts scintillation light to 174 nm.

Effects of Xenon Dopant

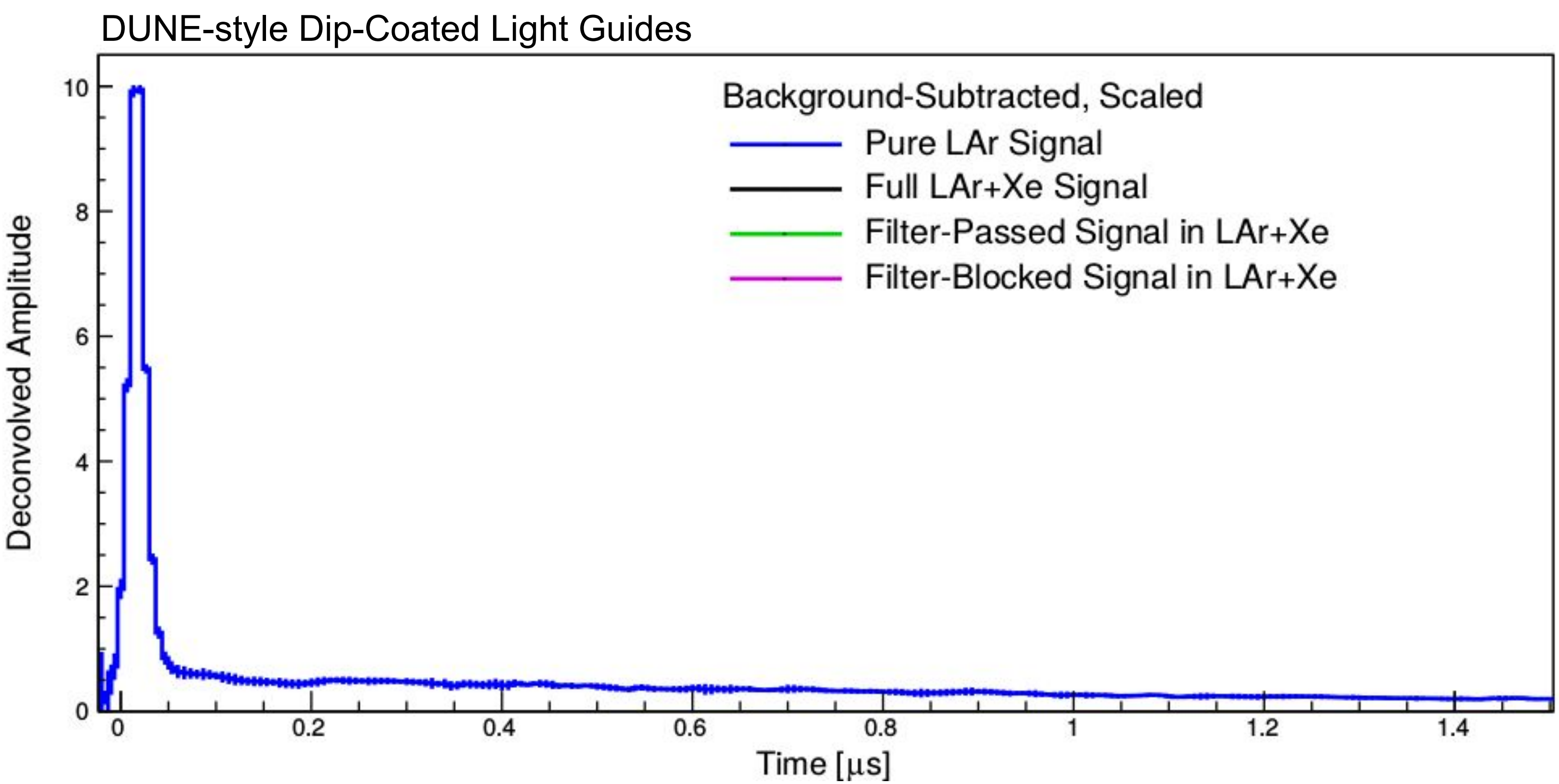
Increasing shift of scintillation to 174 nm with added xenon dopant.



TU Munich 2014-2015

Effects of Xenon Dopant

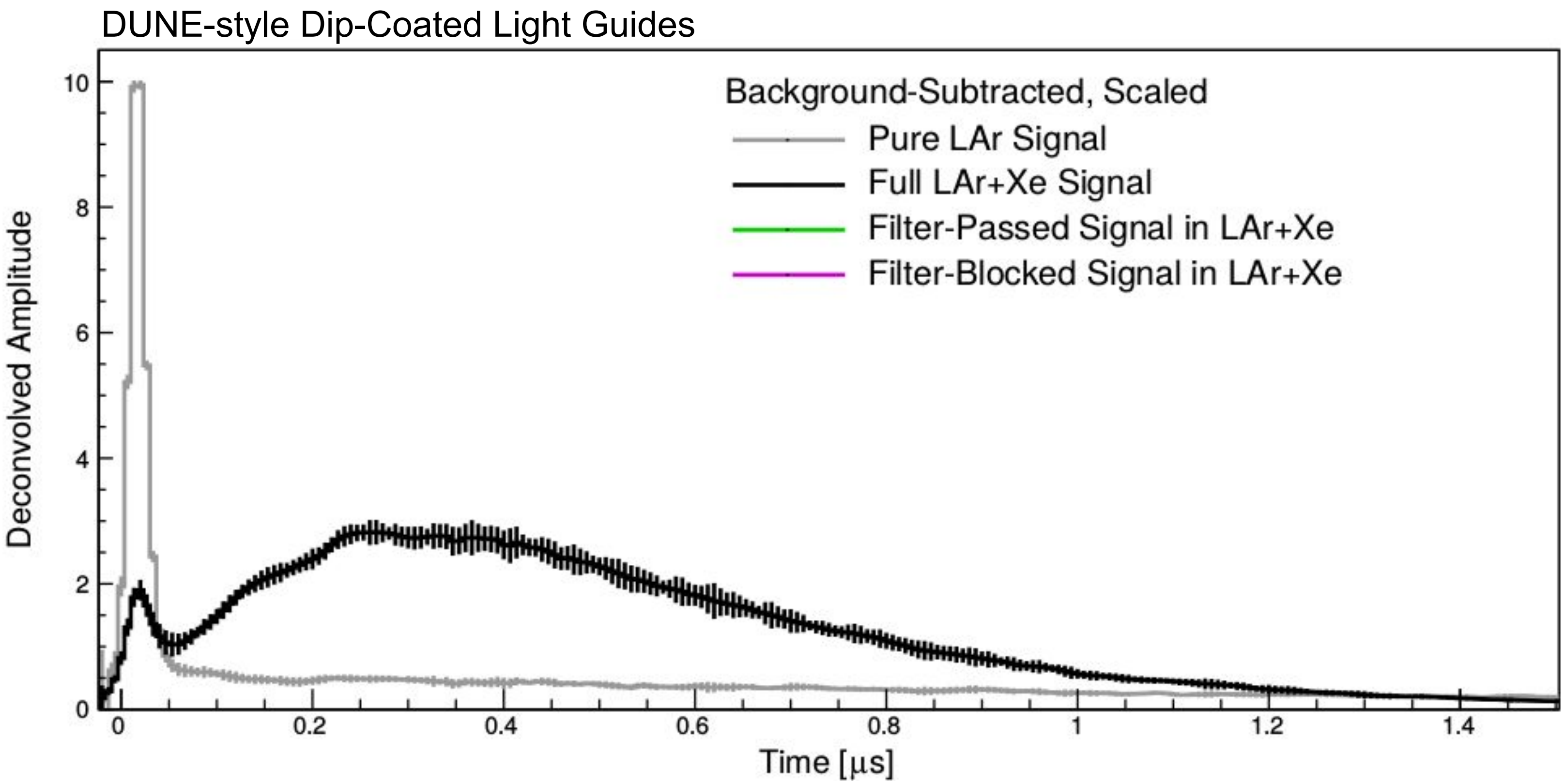
Wavelength structure



PAB (Blanche) 2016

Effects of Xenon Dopant

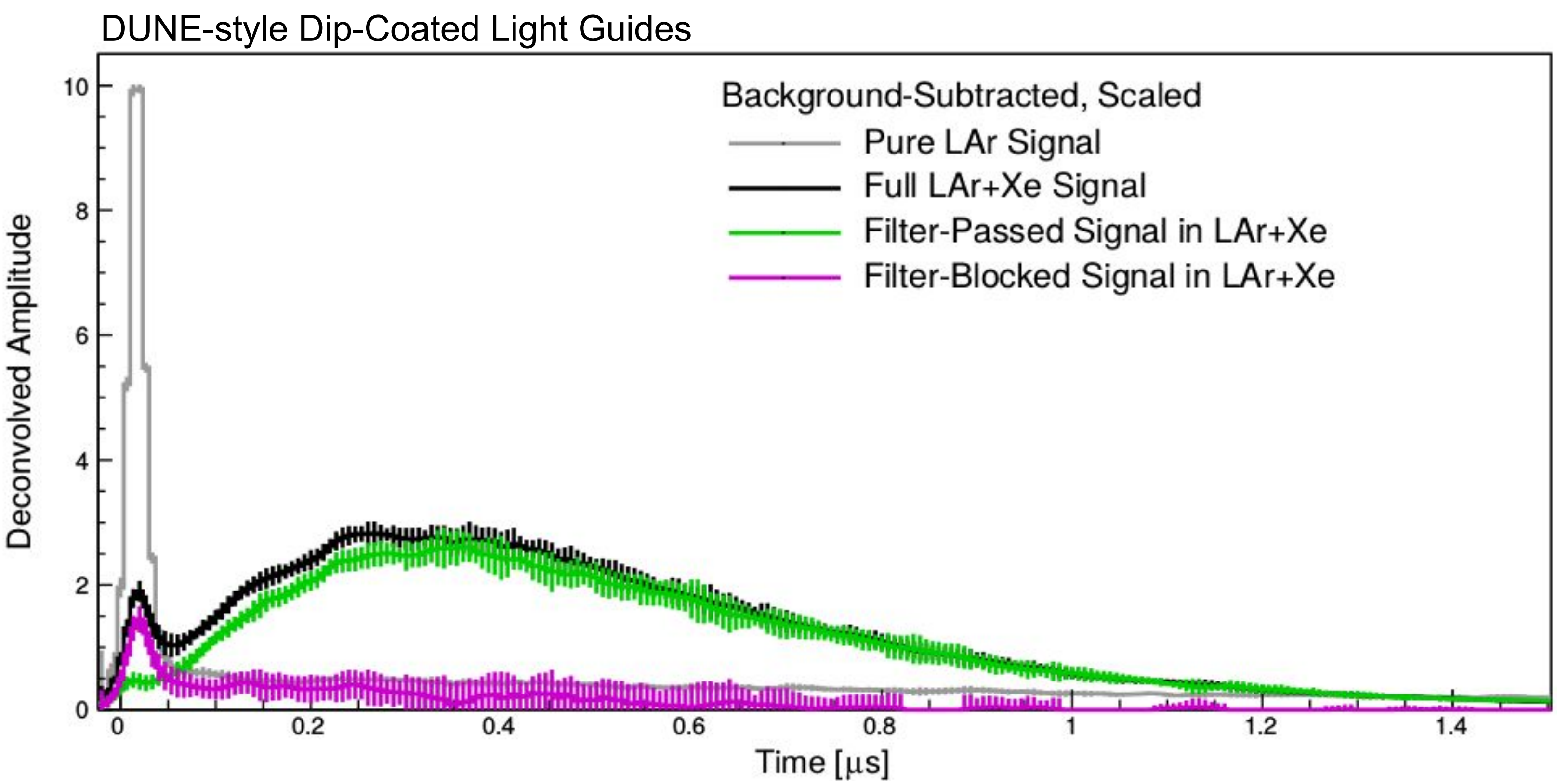
Wavelength structure



PAB (Blanche) 2016

Effects of Xenon Dopant

Wavelength structure

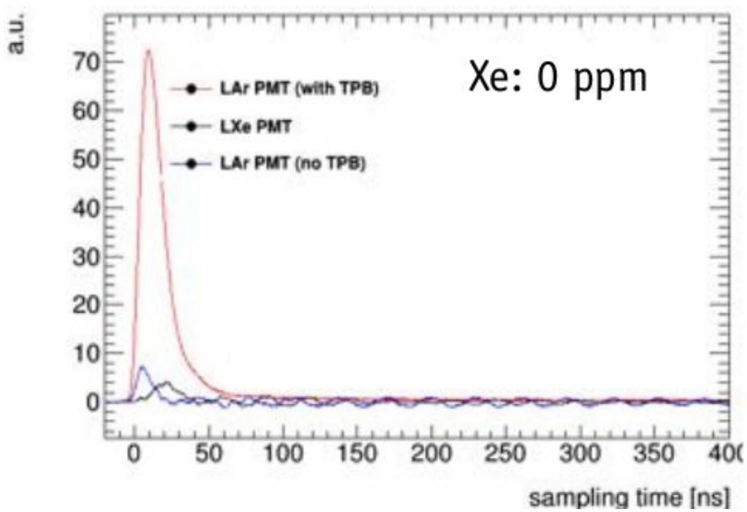


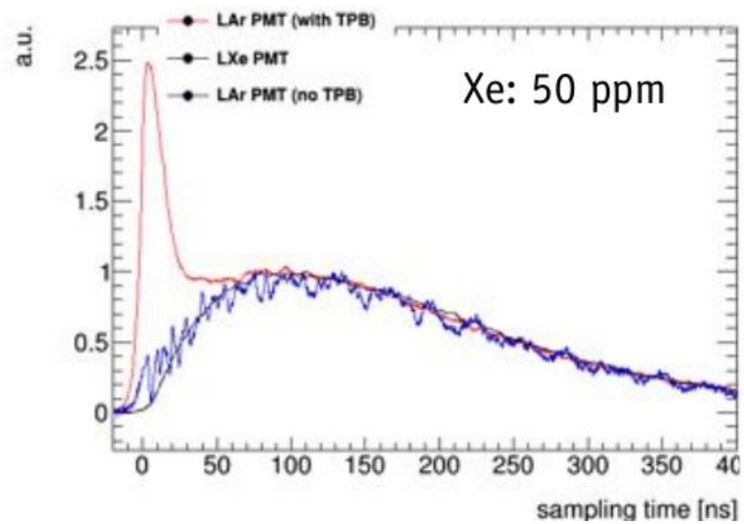
PAB (Blanche) 2016

Effects of Xenon Dopant

Wavelength structure

Light detected with PMTs (sensitive to different wavelengths)

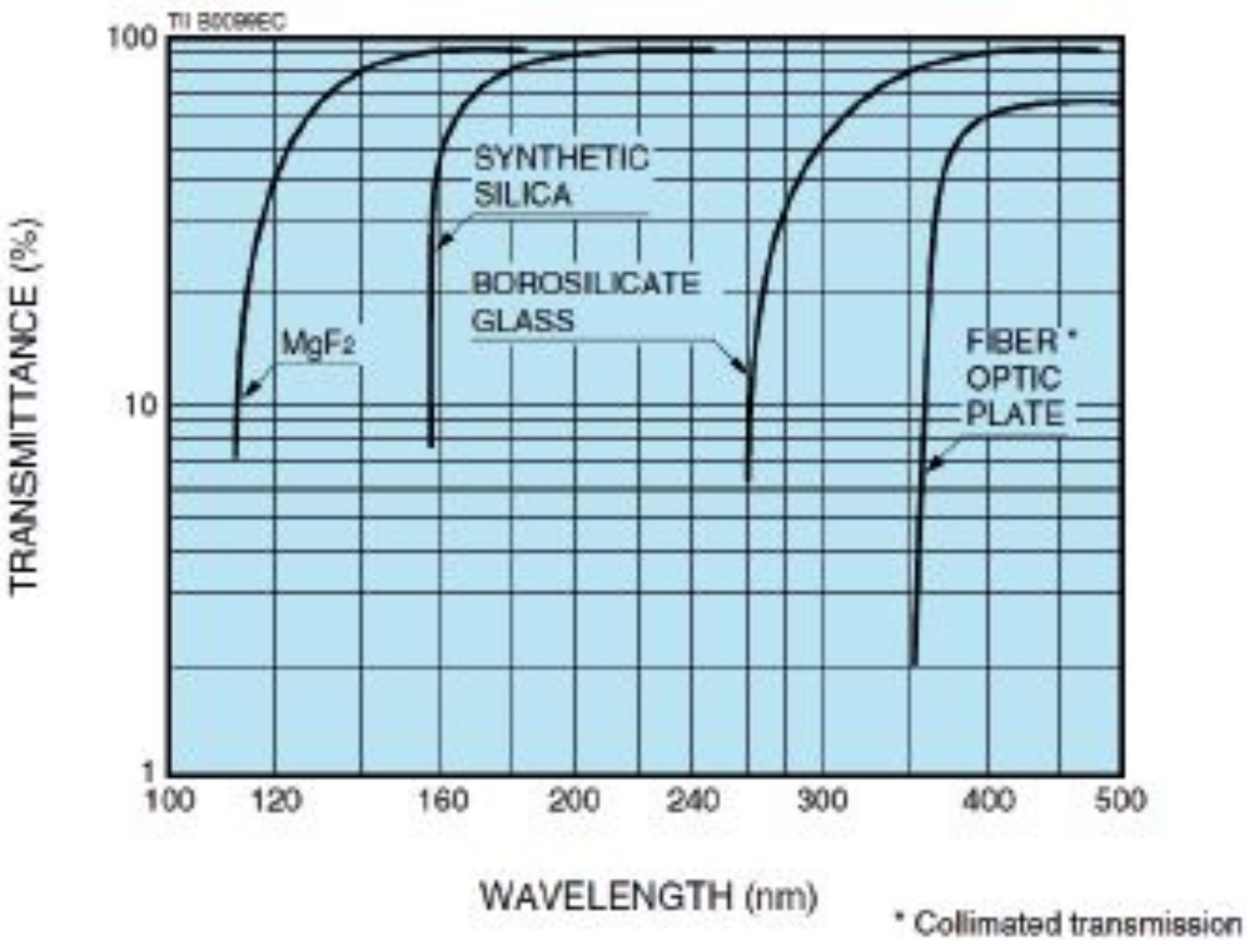




V. Ippolito, F. Pietropaolo, H. Wang, Y. Wang, 2018

Technology Benefits

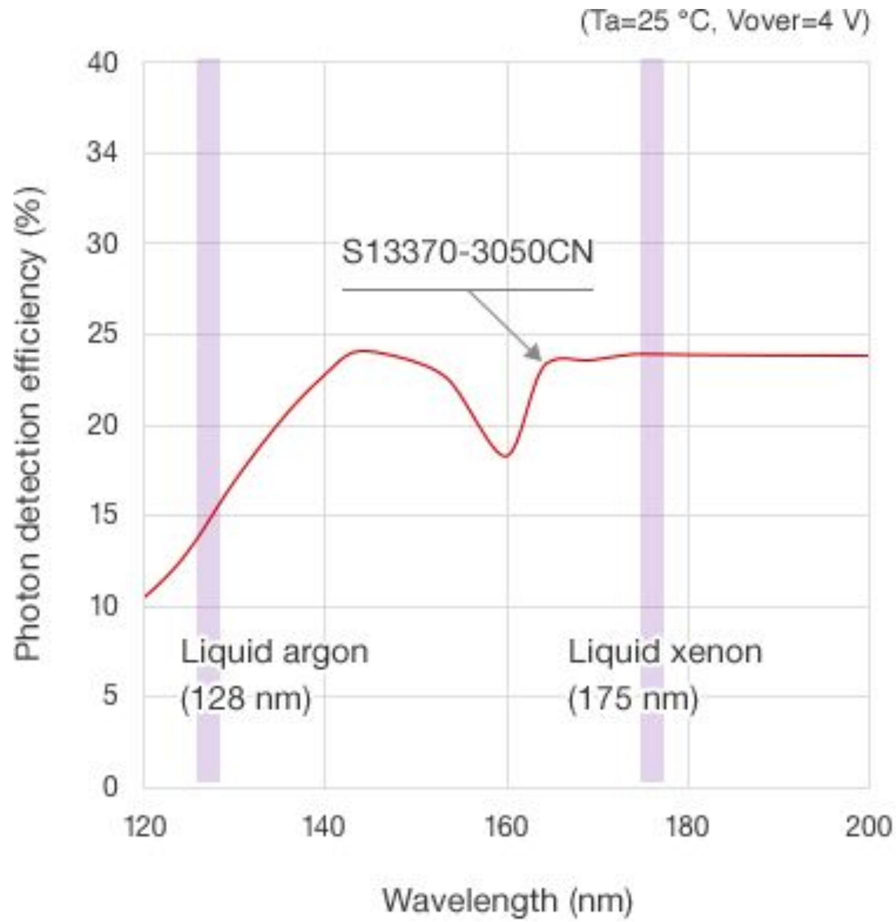
Less expensive glasses are transparent to longer-wavelengths.



Technology Benefits

Growing variety of direct VUV-sensitive detetctors (PMTs, SiPMs)

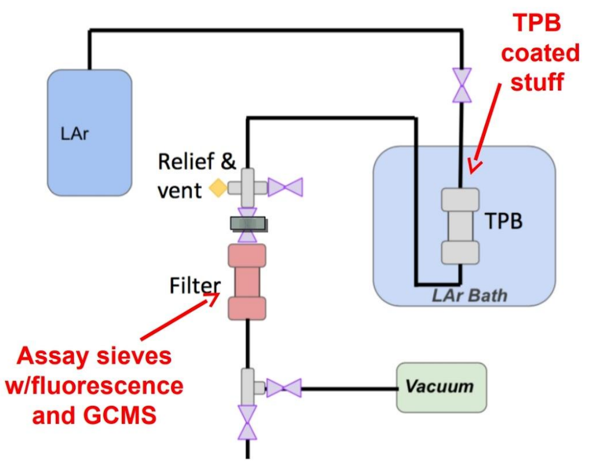
Hamamatsu MPPC S13370/S13371 series

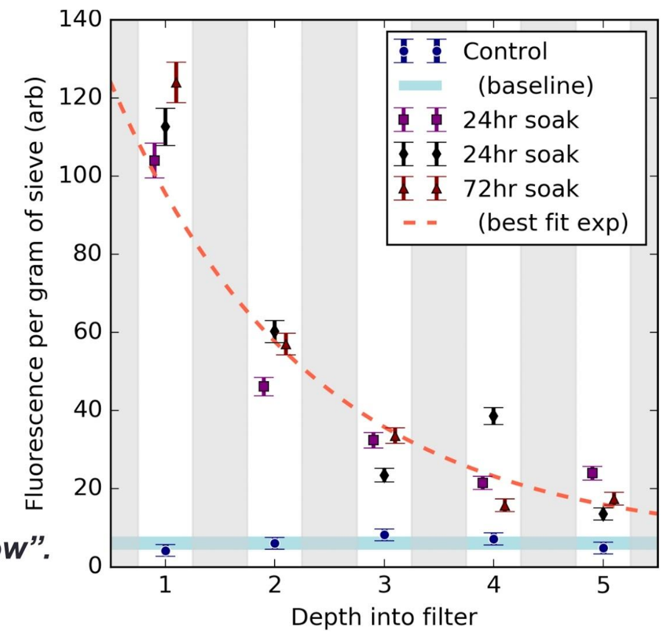


Technology Benefits

Reduced dependence on wavelength shifters

- Indications that TPB can dissolve into LAr





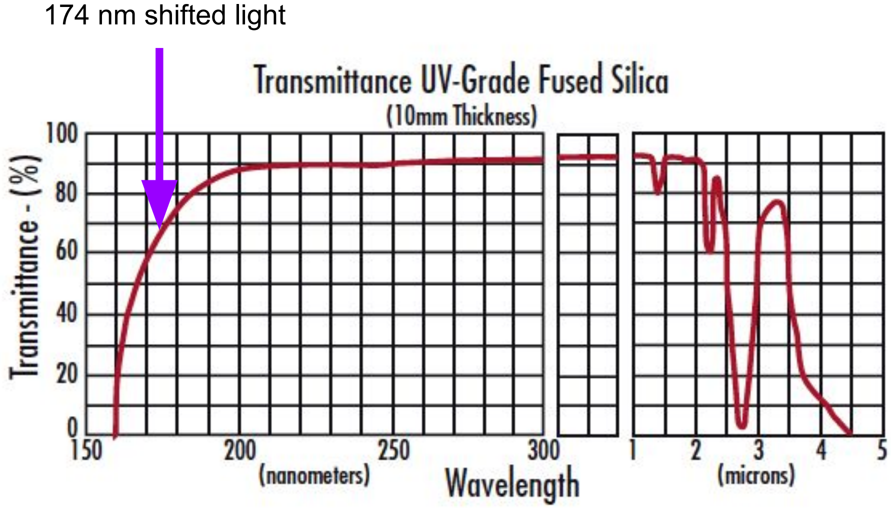
10ppb may be enough to make argon "glow". Tests at UT Arlington ongoing.

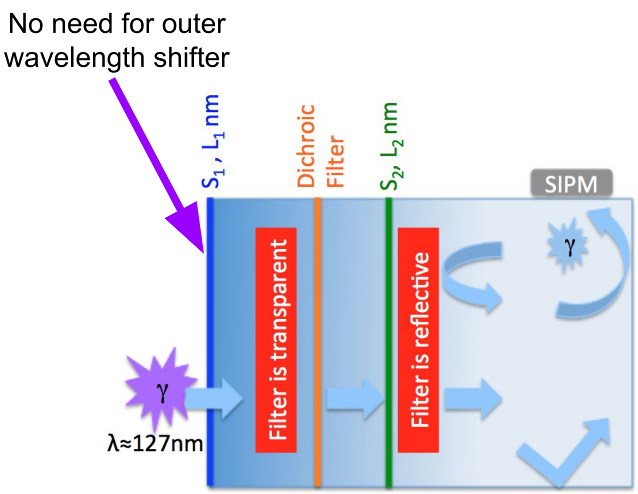
J. Asaadi et. al, https://arxiv.org/abs/1804.00011
B.P.Jones at LIDINE 2017 https://indico.physics.lbl.gov/indico/event/545/contributions/1200/

Technology Benefits

Remove outer wavelength shifter from ARAPUCA modules

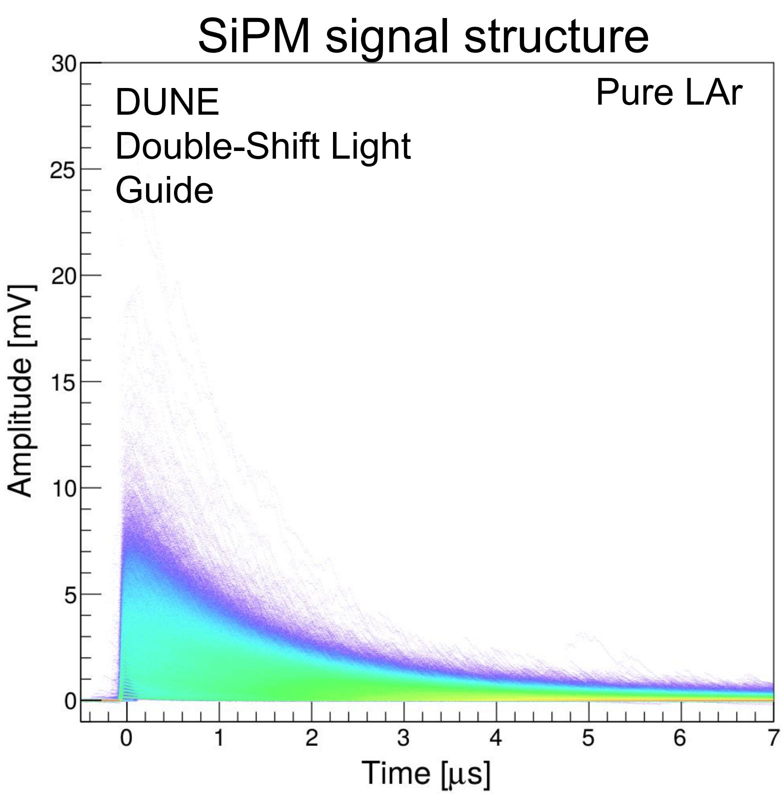
- UV light passes directly into light-trapping volume

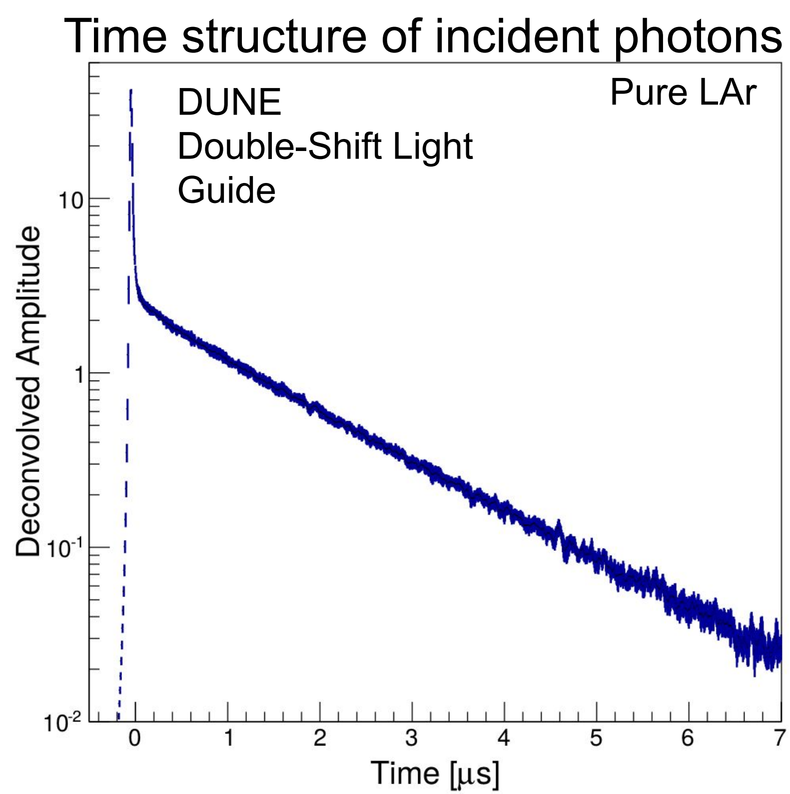




- Reduced cost / construction complexity
- Remove light exposure mitigation requirements (light filters)

Signal Benefits





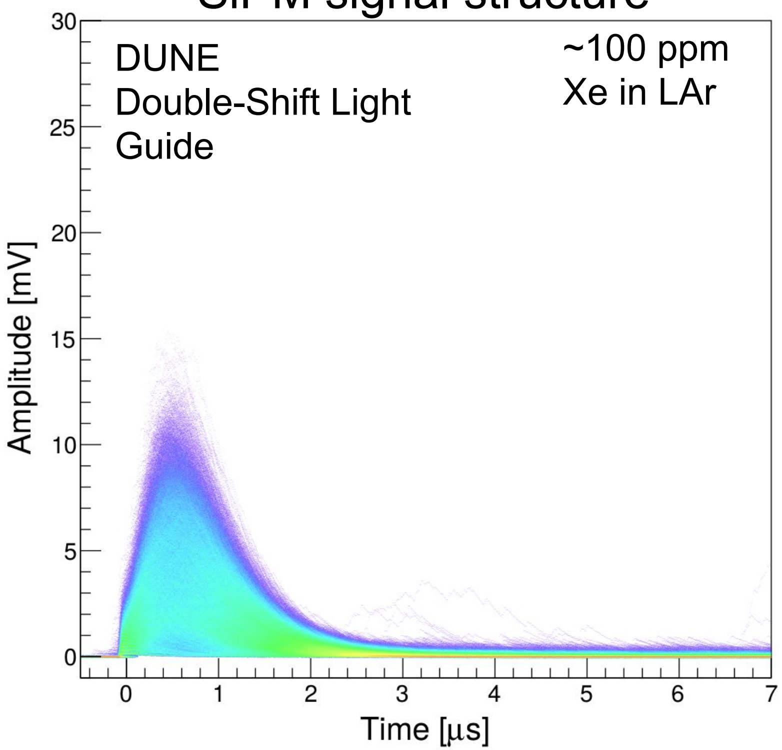
PAB (Blanche) 2016

Signal Benefits

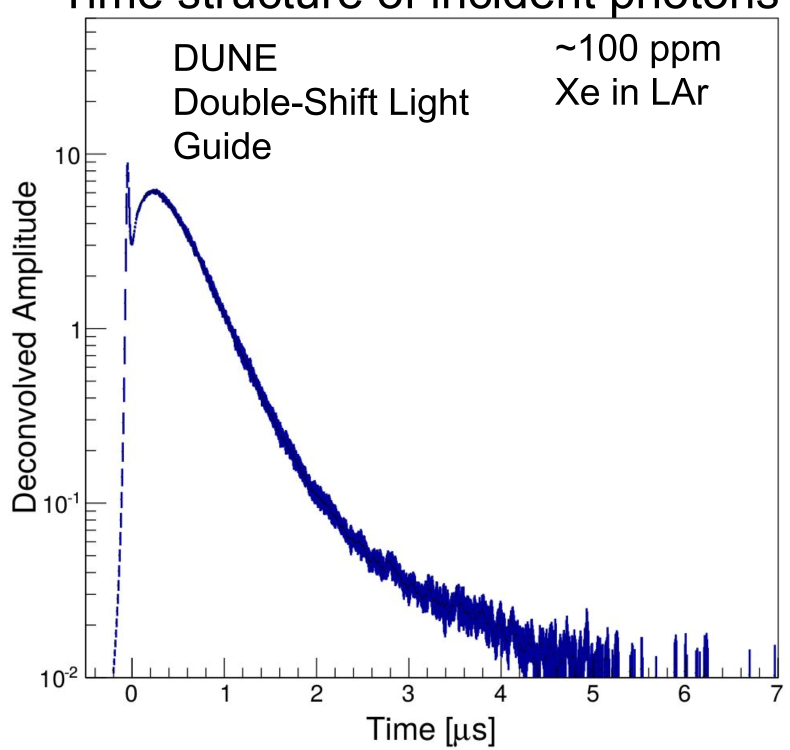
Timing

- Reduced flash overlap from late-light signals
- Maintains sub-TPC-tick leading-edge timing resolution

SiPM signal structure



Time structure of incident photons

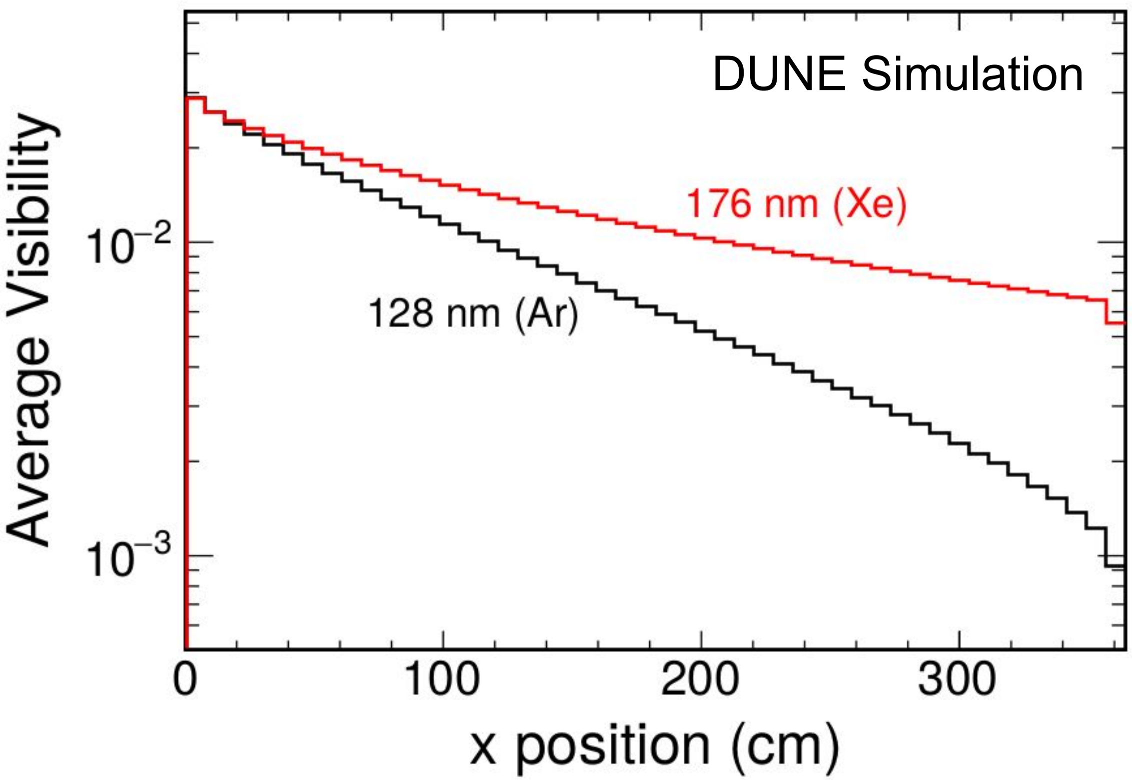


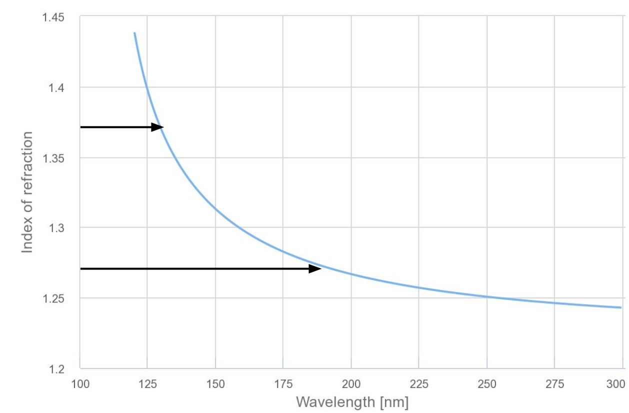
PAB (Blanche) 2016

Signal Benefits

Uniformity

- Reduced Rayleigh scattering improves visibility near CPA





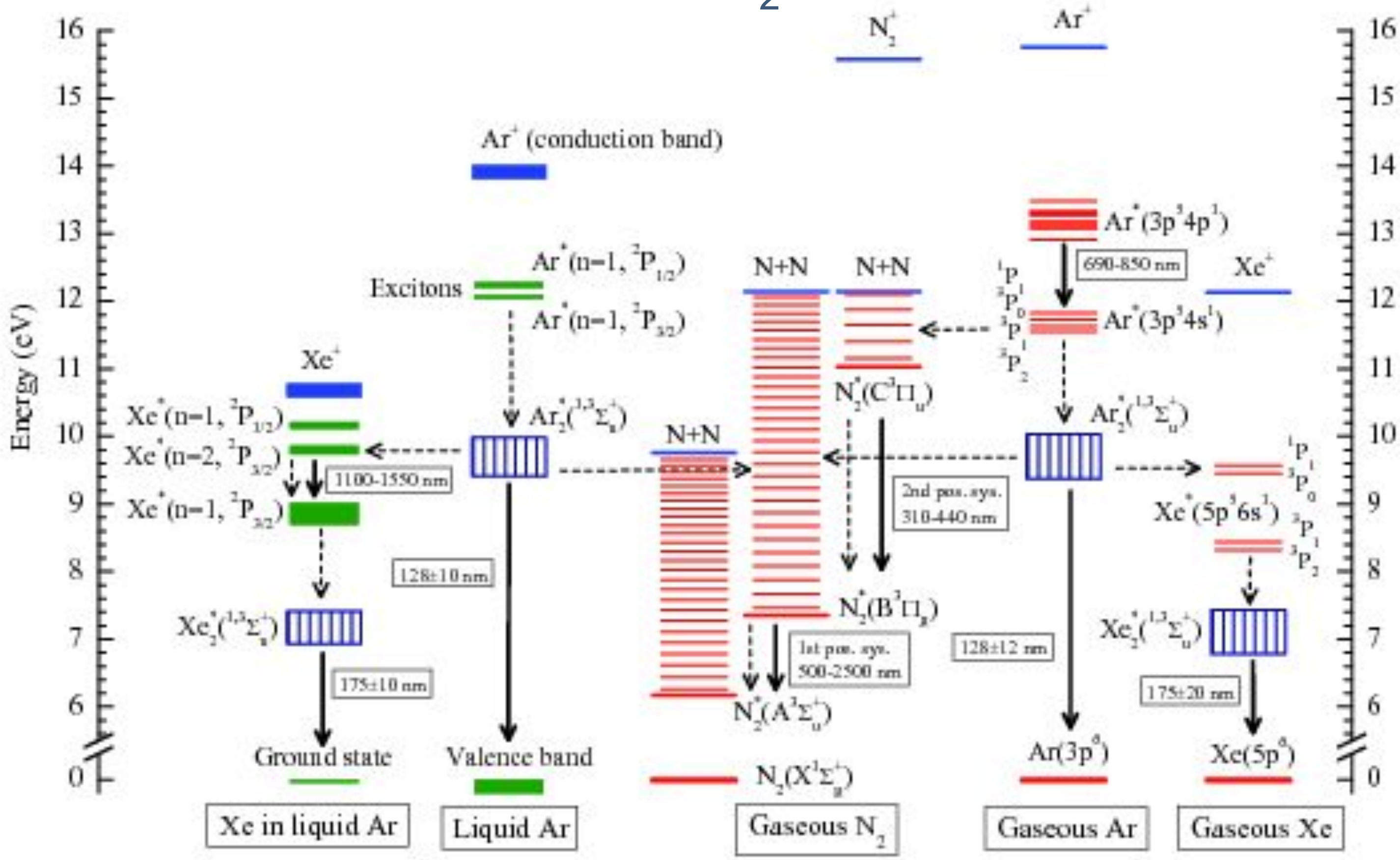
$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\boxed{\lambda^4}}\left(\boxed{\frac{n^2-1}{n^2+2}}\right)^2$$

~6 times longer Rayleigh scattering length

Signal Benefits

Mitigation of Contamination

- Excitation transfer faster than N_2 quenching

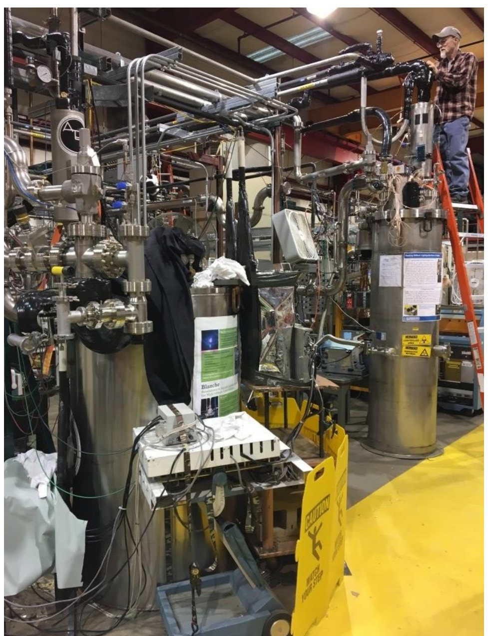


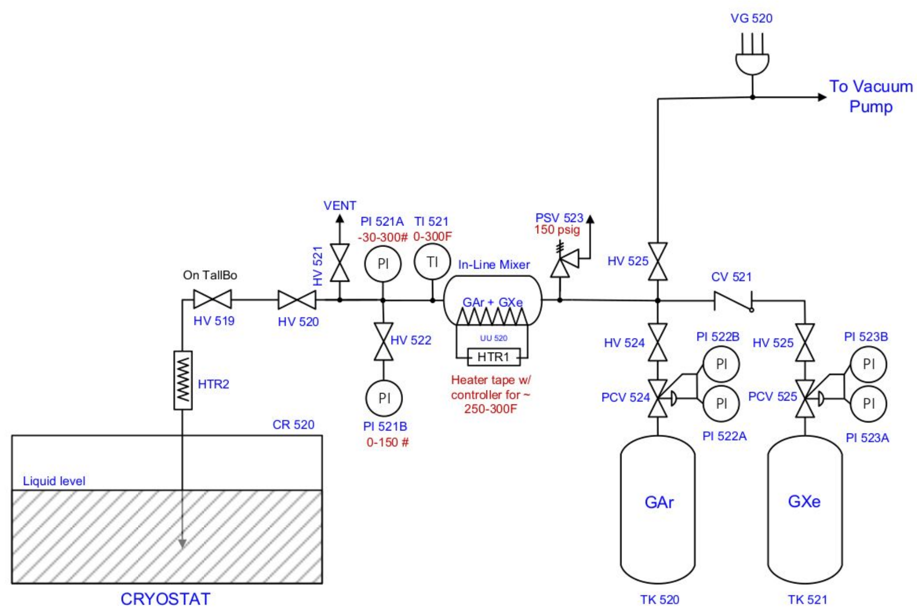
Syracuse University

Challenges

Injection

- Inject low-concentration xenon gas directly into LAr
  - Premix GXe into GAr and heat to prevent freezing
  - Successfully operated at PAB

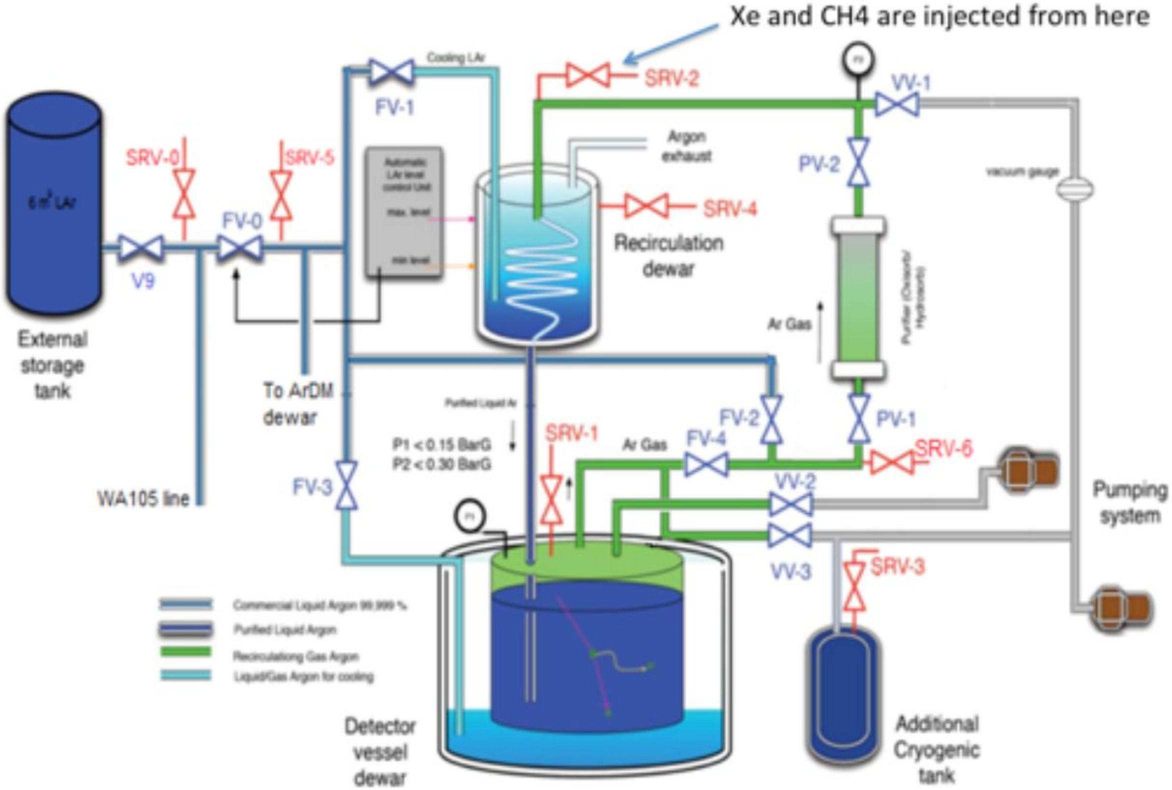




Challenges

Injection

- Inject xenon gas to argon gas prior to condensation
  - Available and successfully operated at CERN



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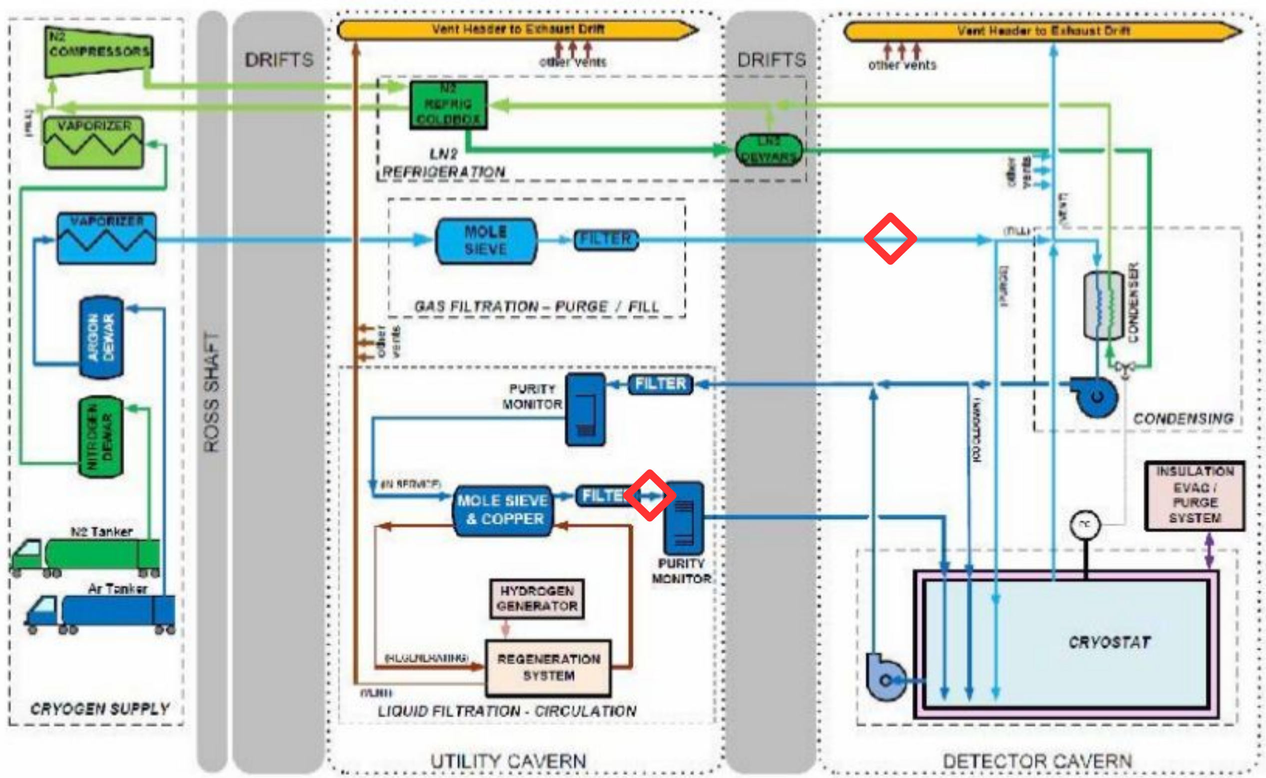


Possible locations for GAr+GXe premixing

Challenges

Maintaining

- Indications are that Xe remains stable in solution.
  - Observed scintillation structure at Blanche 2016 consistent with losses only from LAr boil-off through monitoring devices. This was observed over the course of about 2 weeks. [DW]
  - 3000 ppm solution stable over ~56 hours. [D. Rudik, LIDINE2019]
- Currently no plans to top off a Far detector module. This means that over time there will be LAr loss.
  - This was estimated to be ~1"/yr which would represent a 0.2% change/yr in the Xe doping fraction. [Alan Bross & Mark Adamowski, FNAL]

Monitoring

- Residual gass analyzer {Challenging above 100 AMU}
- Scintillation time structure

Challenges

Cost

- A detailed cost estimate would require an evaluation of flow rates, piping design, etc., but that infrastructure is likely to be small compared to the cost of Xe.

- Xenon would likely cost ~ $20k/(ppm Xe doping level) for one Far Detector module.

- Optimization of xenon doping level needed, but likely in the neighborhood of ~100 ppm.

from: Alan Bross & Mark Adamowski, FNAL

Open Questions

What impact will the xenon have on

- Charge yield?
- Charge attenuation?
- HV stability?

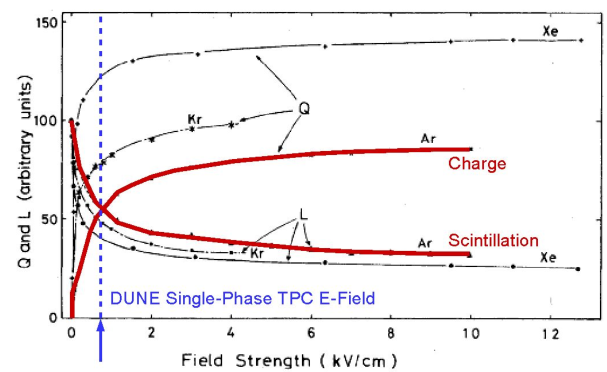
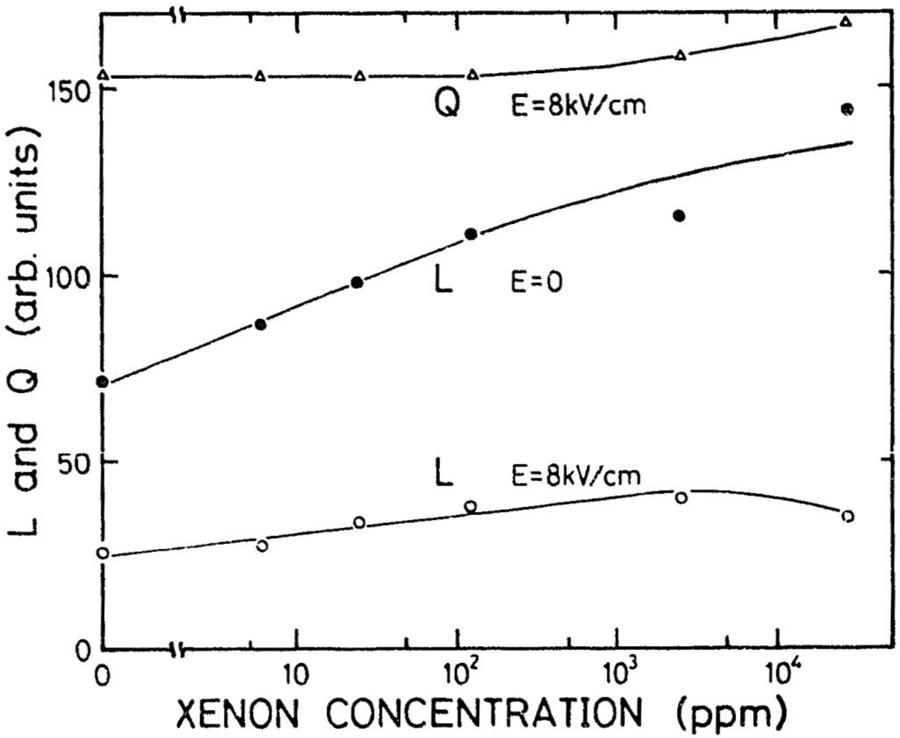


FIG. 2. Variation of relative luminescence intensity L and collected charge Q in liquid argon, krypton, and xenon vs applied-electric-field strength for 0.976- and 1.05-MeV electrons.

S.Kubota et al., Phys. Rev. B20 (1979), 3486



Indications that total light yield increases with xenon concentration.

Light yield suppressed by charge production in E field.

Effects at 500 kV/cm not thoroughly explored.

Suzuki, et al. 1993

Recent and Upcoming Investigations

ProtoDUNE-SP

- Xenon injection planned for January 2020
- Likely ~100 ppm concentration
- Investigate impact on TPC and mitigation of N_2 contamination
- Test response of X-ARAPUCA to scintillation signal

CERN teststand (FLIC)

- Small-scale combination TPC and PDS
- Investigating mitigation of ~5ppm N_2 contamination using Xe dopant
  - *Preliminary results quite promising!*
- Testing response of S-ARAPUCA and X-ARAPUCA modules

Summary

Small concentration of xenon has several benefits for a large LAr TPC

- Reduced ambiguity from late light,
- Improved uniformity across drift direction
- Potential for increased light yield and efficiency
- Simplified photon detector design options
- Possibility to mitigate light loss from N_2 contamination

Does offer some challenges to understand

- Injecting, maintaining, and monitoring
- Concentration should remain stable; studies needed to confirm.
- Monitoring is a potential challenge; more investigations are needed.
- Cost should be reasonable for low xenon concentration.

TPC Interaction (unlikely, but should be investigated)

Ongoing studies with teststands and ProtoDUNE